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INTERFACE OF MATERIALS AND STRUCTURES
ON AIRFRAMES
PART 1
BASIC DESIGN CONSIDERATIONS

by

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ABSTRACT:

The interface of materials and structures is of particular importance during the early design phases of an aircraft when decisions regarding the choice of material and corresponding structural configuration have to be made. This part of the design process is considered from the viewpoints of materials, structures, and design engineers. While well-defined problems in each of these fields are in the hands of competent specialists, it is shown that major problems also exist in the ill-defined regions between these specialties and have beckoned vainly for any systematic approach toward their solution. These problems are identified and steps toward their solution are recommended in some detail.

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This report forms the first part of an investigation under the title Interface of Materials and Structures on Airframes. It is sponsored by the Naval Air Systems Command under the cognizance of the Structures Administrator.

The investigation has been conducted at the Naval Postgraduate School, Monterey, California. It included a good many visits with government agencies, research organizations, and aerospace companies. The willingness of all individuals who were contacted -- too many to be listed here -- to discuss problems in their fields, to give generously of their time and experience, and to extend a spirit of full cooperation, deserves the very highest appreciation.

I. INTRODUCTION

1.1 Purpose

It is the basic purpose of this report to provide a systematic survey of fundamental problems regarding the interaction between materials and structures on airframes.

As a second purpose, attention is focused on practical implications connected with the utilization of new materials. Problems of interface between materials and structures are of special importance in this respect but no systematic attempt seems to have been made to identify them in their overall context and to clarify a basic method of approach.

As a third purpose, special consideration is given to the line of thinking which leads to the establishment of controlling parameters for the selection of material and structural configuration. This is closely connected with fundamental aspects of the design process.

In view of the complexity of the subject and of the lack of a well-defined basis, a descriptive approach has been chosen for this report. This may serve as a first step toward clarification of general concepts and as a basis for discussion in a field which is still rather vague. A further report is planned as an additional step, with the objective to establish a more formalized procedure for design considerations.

There is a great diversity of viewpoints and opinions in the field of interface between materials and structures. Nevertheless, this report contains clear conclusions and recommendations regarding present problems, as shown in Sections 9 and 10, despite the basic fact that there is no objective method available to judge their merit. Some of them may not go unchallenged. If this should be the case, it would serve a final purpose of this report: to stimulate discussion which may eventually lead toward a consensus of opinions on the fundamental issues.

Note: The investigation is limited to basic considerations for aircraft and missiles and does not include specific problems of composite materials.

1.2 Historical Background

Interface of materials and structures is the very essence of structural design. In the past, material selection was a rather unsophisticated process and hardly any basic problem existed. Only few materials were serious contenders and the choice between them was frequently determined by secondary reasons. Production facilities and experience weighed heavily against

experimenting with new materials and the change from wood to aluminum construction, for instance, took place gradually over a period of two decades. About as much time elapsed in the development of titanium between its first application to firewalls in the late 40's and larger-scale structural application in the 60's -- in spite of development expenditures which amounted to several hundred million dollars.

This situation is changing rapidly. With the advent of supersonic flight over extended periods of time, a situation has to be faced where environmental and operational conditions vary from one part of the aircraft to another so that there is no one material and structural configuration offering an optimum solution. Each structural component has to be considered individually. A very large number of aluminum, titanium, steel, and beryllium alloys and many types of structures are at our disposal for the supersonic flight regime, and some of them are becoming competitive even for subsonic flight. The introduction of composite materials will multiply the complexity of this situation.

The present status can be characterized as follows:

Selection of an optimum combination between material and corresponding structural configuration presents considerable mathematical difficulties which have been recognized but will not be solved in the immediate future although a great amount of significant work is being done by structures specialists developing methods for structural optimization. Other structures specia- ists have worked on methods for structural analysis while materials special- have concentrated mostly on investigating failure of materials.

However, the field of interface between materials and structures has not been given much attention. Only very recently a greater concern began to become visible about the reluctance of the aerospace industry to introduce new materials for structural design. There are even some symptoms that this concern may turn into a fashionable trend as terms like "materials barrier" and "iron curtain" are applied.

1.3 Basic Considerations

Interface of materials and structures, as the name implies, is concerned with the large field of applying materials to structures. This includes material properties, production techniques, structural analysis, and structural testing as some of the most basic ingredients. The dominant aspect, however, is the problem of determining the proper combination of material and structure. This requires intimate contact between the two diciplines of materials engineering and structural design which have been working quite independent of each other until not many years ago.

It had been the accepted procedure that the materials engineer provided the basic properties of a desirable material and the structures engineer built his structures correspondingly. The lack of understanding for the

other's problems was the root for much costly and even catstrophic experience in the fields of fatigue and stress corrosion. The structures engineer did not specify details of operational and environmental conditions because he did not realize their influence on material characteristics, and the materials engineer did not emphasize such information because he did not realize its vital importance for structures. As an example for this basic misunderstanding, for a long time the structures engineer kept asking for materials with high ultimate tensile strength,not realizing the high penalty he had to pay for this property which has become quite unimportant in the meantime.

With a large number of new materials available, each having different characteristics under different operational and environmental conditions, and with a large range of these conditions for various components of a high-performance aircraft, the interface of materials and structures presents a new complexity of problems. The need for closest contact and coordination between materials, structures, and design engineers has been recognized as an indispensable prerequisite which, however, is not always easily effected due to the different backgrounds. Fortunately, circumstances are in favor of increasingly close cooperation.

Materials engineers have the basic responsibility for integrating materials in design and production and recently had to occupy themselves very thoroughly with fatigue and stress corrosion and how these are influenced by structural configuration, environment, and loading. As a consequence, they are becoming very conscious of the implications of material application and of the need for well-defined material evaluation techniques.

Structures engineers have the basic responsibility for airworthiness and structural analysis and have been much concerned with failure analysis in the same fields of fatigue and stress corrosion. As a consequence, they have had to familiarize themselves with material characteristics more thoroughly than before.

In spite of this general trend, most of the work has been conducted by specialists for specific objectives. They have seen their prime responsibility from the perspective of their own discipline. Although the need for basic understanding of the problems in adjacent disciplines is increasingly being recognized, a systematic effort toward coordination in the gray areas between the established disciplines has not yet been made.

We should also realize that such considerations touch upon some very fundamental questions. We are in a period of transition as we are becoming aware that complexities of our technological world in general, and of interface between materials and structures as a particular example, go beyond the capacity of an individual's mind. We face, much more than ever before, the problems of coordinating the work of a team of specialists,

incorporating computerized methods as an auxiliary tool, and establishing the proper place for human creativity, ingenuity and judgment. In the field of interface between materials and structures we are in the fortunate position that we can anticipate and recognize new developments in materials, structural optimization, and computerized methods and that we are beginning to become aware of the limitations in our present situation. This is a propitious basis for considering some fundamental implications.

1.4 Method of Approach

Interface of materials and structures plays a particularly significant role during the early phases of aircraft design. At this time the basic design decisions are made and it is not easily possible to change these decisions at a later time. For this reason, the present report considers firstly the situation as it exists in the three fields of materials, structures, and design during the early design phases leading up to a design proposal. Basic complexities of the problem are recognized by realizing that

a. material characteristics depend on component application, including processing, environmental and operational conditions-- i.e., data which are frequently not available in early design stages;

b. structural analysis requires consideration of a great many different conditions and structural details -- i.e., a prohibitive amount of work which cannot be done thoroughly in early design stages due to limitations of time and available information;

c. structural design has to be accomplished with full consideration of cost, reliability, potential risks in new developments -- i.e., many factors which are hard to assess quantitatively in early design stages.

Secondly, as a result of these complexities, fundamental decisions regarding material selection and structural configuration are presently based on incomplete information. The corresponding implications are considered from the viewpoint of establishing controlling parameters and describing the technical decision process.

Special consideration is given to the maxim that design is somewhat of an art -- in the sense of a skill acquired by experience. With increasing complexities, however, no single man's experience can cover the whole field any more. The objective is to identify the multitude of influences which have to be considered in structural design.

Thirdly, additional consideration is given to the viewpoints of procuring agency and aerospace industry. The objective is to show that each of them can take the initiative toward solving an essential aspect of the overall

problem.

Finally, conclusions and recommendations are intended to draw attention to basic aspects. The interface of materials and structures presents a problem of prime importance and an attempt is made to show this problem in its overall perspective as well as to identify an approach toward its solution. The report should also serve as a basis for further work in this field.

2. PROBLEM DEFINITION

The interface of materials and structures on airframes presents the problem of

a. recognizing the mutual influences caused by applying a material to a structural component of an airframe and

b. finding a design which represents an optimum combination of material and structure.

Such a definition is quite all-encompassing and calls for additional interpretation to become meaningful:

interface and mutual influences -- these words imply a region between the well-established fields of materials and structures and beyond the traditional responsibilities of materials and structures engineers;

recognizing and finding -- these two words imply two different aspects of the problem: that it has to be recognized before a solution can be found;

applying a material to a structural component -- this implies that a structural component has to be identified by its operational and environmental conditions;

material -- in the context of the present report this is interpreted as not including the specific problems of a composite material which may be considered to present a sub-structure in itself;

structural component -- this implies a load-carrying component which has to be governed by considerations of strength and stiffness;

airframe -- this includes aircraft and missiles but does not consider specific applications in spacecraft, launch vehicles and engines;

design -- this implies the involvement of a third discipline in addition to materials and structures;

optimum -- this includes not only optimization techniques but also considerations whether an optimum consists of minimum weight, minimum cost, maximum reliability, etc;

combination -- this implies that for an ever increasing number of material alloys, manufacturing processes, structural configurations and operational and environmental conditions an extremely large number of possible combinations exists.

It is the summation of these considerations which presents the problem of interface between materials and structures on airframes.

3. MATERIALS

From the viewpoint of interface between materials and structures, it will be appropriate to begin with some basic engineering aspects of material application. Such engineering aspects serve as a guideline for the materials engineer whose responsibility it is, as emphasized in reference 5, to integrate materials in design and production. Establishing basic material properties represents only a first step. Their application to structural components of high-performance aircraft involves much additional complexity, and the following discussion identifies problem areas in this field.

3.1 Material Properties

Research, development, and testing in the field of materials result in the determination of material properties. General agreement exists regarding most of the basic properties but no standardization has yet been established with respect to either terminology or definition of all critical properties. Among a number of similar listings, Table I was chosen from Ref. 1 and may be used for the purposes of the present report to indicate the type of material properties required for structural design.

It should be realized that material properties depend also on the life history of the material. Exposure to elevated temperature over extended time as well as to repeated loads may result in considerable reduction of properties after the component has been in service for some time.

3.2 Application of Material Properties

Table I lists a total of about 70 properties, including mechanical as well as physical, thermal, electrical, fabricational and other characteristics. For many applications, a good part of these properties is not critical and can be disregarded by quick inspection. On the other hand, for high-performance aircraft the critical properties have to be established not just for room temperature and standard atmosphere. A multitude of environmental and operational conditions exists, varying from one component to another. Also processing techniques have a definite influence on material properties. For example, the properties may change for a sheet material after forming or for a bar material after machining.

> Note: The terms "environmental" and "operational" are used differently in various publications. In this report, environmental conditions will mean ambient conditions which may be either natural (atmosphere) or artificial (e.g. fuel) and will include magnitude and duration of ambient temperature, corrosive influences,

radiation, etc. Operational conditions will mean induced conditions which include external and internal loads with the resulting static, fatigue, multi-axial, thermal stresses, etc.

3.3 Component Testing

An obvious conclusion can be drawn from the preceding section 3.2: Material properties per se have to be supplemented by consideration of the material as applied to a certain component, with full regard for environmental and operational conditions and processing techniques. This results basically in the need for a large amount of component testing -- at great expense of time and money. Many combinations of temperature, exposure time, stress, sequence of cycling, corrosive conditions, etc. may be required far beyond the data which the materials producer will supply.

Some of the requirements can be defined only after the design of the component has been determined, resulting in an iteration procedure. This shows that selection of a material during the early stages of design must frequently depend on available data which are incomplete. Potential difficulties are to be anticipated and proper provision must be made for the risks which are involved in uncertainties. The magnitude of such difficulties, which may develop if problems are left unrecognized or unresolved, can easily be illustrated by an abundance of recent examples in the fields of stress corrosion and fracture toughness.

3.4 Material Evaluation Techniques

3.4.1 The significance of material evaluation becomes apparent from the considerations of the preceding section 3.3 which led to the conclusion that material properties must be evaluated in context with design application. This requires close interaction between materials engineer and designer.

The subject of material evaluation techniques is concerned with the testing which has to be conducted to obtain the basic data for applying materials to structures and which goes beyond the establishment of material properties. It comes close to the heart of the interface problem between materials and structures and deserves very special attention.

3.4.2 Reference 2 gives a clear outline of this problem. Due to its fundamental importance, a brief summary of the findings of this reference will be given in the following sub-sections.

3.4.2.1 The starting point is the observation that material evaluation studies are conducted on a broad scale but that there is no agreement on the test conditions and testing techniques which should be used in evaluating materials for design applications. As long as well-considered guide lines are lacking, some measurements are duplicated, others are omitted, and the result is increasing confusion, lost time, and waste of funds.

3.4.2.2 An outlined approach to the problem suggests

as a first step, to extend previous work identifying vehicle components and their corresponding design environment;

as a second step, to group design criteria into major categories (e.g. criteria for static strength, fatigue, thermal stress, fabricability, surface protection, etc.) and identify the corresponding available testing techniques;

as a third step, to consider the need for new or improved evaluation techniques which may be required in connection with the vehicle components identified in the first step;

and as a fourth step, to discuss trade-off factors with respect to weight, fabrication cost, material cost, product life and their relative importance with regard to specific components.

3.4.2.3 As a conclusion, the formation of a committee is recommended for the purpose of following an application-oriented approach toward solving this large and important task.

3.4.3 In agreement with Section 3.4.2.3, a committee was formed early in 1967 and a description of its efforts is given in Reference 1. From the viewpoint of interface between materials and structures, the following aspects are of special interest:

3.4.3.1 A system has been formalized which may be used as an approach toward solving the problems of material application and evaluation. This system ranges through the development of a component from preliminary concept to final design. Three phases can be distinguished:

Firstly, the material screening phase. This calls for screening properties which are used to establish absolute minimum requirements -- permitting "yes" or "no" answers whether basic properties are satisfactory and, therefore, narrowing the choice of materials;

Secondly, the material selection phase. This calls for selection properties which are the basis of trade-off studies of the remaining number of candidate materials;

Thirdly, the detail design phase. This calls for design data properties which permit design and fabrication of a component to function with a specified reliability. These comprehensive and costly data of the third phase have to be established only for the selected material as applied to a specific component.

Such a system indicates clearly the need for identifying significant properties for various design phases. Different components of the same material will generally require some different properties for each design phase depending on operational and environmental conditions.

3.4.3.2 As a further step, a data processing system has been proposed for manipulation of material evaluation data. Its purpose is to develop computerized answers to the typical questions asked by material producers, aircraft manufacturers, and government agencies regarding material development, design application, and evaluation. The input consists of three data banks which will have to be established for material properties, material evaluation techniques, and application analysis. (General considerations about material selection are shown in Ref. 3.)

3.4.4 It must be noted, however, that much additional work will be required in the fields of material evaluation techniques, application analysis and trade-off methods. The materials engineer is responsible for material evaluation techniques and the design engineer for trade-off methods. Material application, however, is the joint responsibility of materials, structures, and design engineers. It is inseparably connected with design considerations and will be further discussed in Section 5.

Regarding material evaluation techniques, the scope of the problem may be appreciated by quoting from Reference 2:

"... test techniques should be identified, suitably referenced, classified, and comments noted as to their suitability. The latter effort may prove to be more difficult than it sounds since not all test techniques are universally accepted, nor is there complete agreement as to the usefulness of many that are. Nevertheless, it would be valuable to summarize the situation with the intent that 'problem areas' that are identified could be referred to some appropriate group for further action. A case in point is the lack of correlation which has been observed between laboratory tests and service experiences in problem areas such as stress corrosion ... The main purpose is to determine which of the many evaluation test techniques are applicable

to which component, and of those, which appear to require improvement. It may be, for some components, that no satisfactory evaluation test technique exists ... Attention could be given to assessing the trade-off between accuracy, speed, and cost of testing for various types of design criteria."

3.4.5 Material evaluation techniques have presented a very evasive subject. A major reason can be found in the scope of the problem. The best approach toward a solution may be found by subdividing the overall problem into well-defined sub-problems. The solution will have to be found by materials engineers.

3.5 Test Data Information System

An enormous amount of test data on material properties is continuously produced by a large number of material producers, component manufacturers, and research agencies. The tests are conducted on many different components under various environmental and loading conditions. The resulting information must be collected, interpreted, stored, and disseminated. Such an information system has to form one of the ingredients of a data processing system as suggested under 3.4.3.2 or of any other systematic future developments.

The magnitude of this task may be appreciated by considering just one aspect of it: The interpretation of test data. A large number of data on similar tests may produce considerable scatter of test results. Such data are not very useful unless they are interpreted with respect to test conditions in order to find a possible explanation for the scatter band.

Considerable effort has been extended in this field, and the Defense Metals Information Center presents an outstanding example of this work. Much more still has to be done but progress is being made. Centralization of this information should not be necessary due to recent developments in communication. On the contrary, it may be advisable to have specialized fields under the cognizance of different agencies which have to assume corresponding responsibilities and which can serve as basic sources for any information in their respective fields.

A solution will have to be found inside the materials community. There is no easy remedy within sight but clear recognition of the problem of information proliferation will have to result in appropriate steps. Two particularly important aspects are:

a. Data generated by government contracts should be made available systematically to a data bank for distribution and utilization;

b. Proprietary data developed within the industry should be exchanged more freely along the lines discussed in Section 8.3.

3.6 Utilization of New Materials

Development of new materials to the point of applying them in aircraft design has been an extraordinarily slow process. The reasons are implicit in the preceding considerations. An enormous amount of testing is required to establish material properties, component applications and evaluation techniques. The risk of using any new material is frequently prohibitive until these tests have been thoroughly conducted and experience has been gained. This means that a new material becomes actually available only after is has been thoroughly tested and its conformity with production standards has been established.

In the case of titanium, highly disturbing surprises still occurred after more than a decade and a half of intensive, high-cost, and large-scale development work. Many of the lessons learned in the development of titanium are significant and applicable to the development of other materials (Ref. 4) -- although it must not be expected that such generous funding will often be available.

The growing concern about the slow rate of integrating new materials in aerospace structures resulted in the appointment of a task group by the NASA Research and Technology Advisory Subcommittee on Materials in late 1968. Its task was to (1) ascertain the validity and seriousness of the alleged applications gap, (2) identify potential reasons for its existence, and (3) propose measures for its alleviation. The findings of the task group were reported to the Committee in References 5 and 6, arriving at the following general conclusions:

a. The rate of integrating new materials in systems design is extremely slow;

b. Substantial gains in system performance can be obtained from use of advanced materials;

c. The failure to use advanced materials may curtail the capabilities of advanced flight and weapon systems and may severely reduce the superiority margin in case of a national emergency;

d. An improvement of this situation is possible. Since it involves not solely the materials community, but also design, systems planning, and procurement, it requires an interdisciplinary program coordinating the adjustments in each concerned discipline.

The following recommendations, in the order of significance, were tentatively formulated:

a. Formal adoption, activation, and funding of independent "applications development" programs, in lieu of prototype systems;

b. Strong orientation of materials R&D toward product requirements, with emphasis upon future generations of systems;

c. In the advanced materials R&D phases, gradual reduction of the number of pursued materials in favor of more extensive properties verification;

d. Establishment of strong materials engineering segments with adequate authority, in government agencies and industry, supported by appropriate programs in educational institutions;

e. Increased incentives in systems contracts for the effective utilization of new materials;

f. Definition of materials capabilities, in addition to customary properties, in terms of systems performance, comprising technical and nontechnical criteria and tradeoffs;

g. Early definition of advanced systems requirements by systems planning and design, to include material target capabilities, as basis for (a), (b), and (f);

h. Use of projected materials capabilities and costs in conceptual systems studies and advanced design;

i. Increased design adaptation to new materials and processes;

j. Definition of cost effectiveness for total systems life;

k. Release of development models in advance of production models;

l. Improved communication and data exchange between disciplines and organizational segments.

Besides, it was strongly recommended to initiate an in-depth follow-on investigation.

The preceding conclusions and recommendations as quoted from the NASA Research and Technology Advisory Subcommittee on Materials indicate the difficulties which have to be faced in introducing new materials. These conclusions and recommendations coincide with subsequent considerations of the present report. The reason is, of course, that utilization of new materials is a particularly obvious and important aspect of the overall problem of interface between materials and structures.

3.7 Summary of Problem Areas Regarding Materials

3.7.1 From the viewpoint of interface between materials and structures, the main problem consists of the following gap of information: On one hand, the material manufacturer provides basic data on a new material in general; on the other hand, the aircraft manufacturer requires specific data on the material as it is applied to a given aircraft components.

This gap has to be bridged by additional component testing which is often excessively expensive and time-consuming for a specific component. A systematic approach is needed and four problem areas appear particularly significant:

a. Analysis of material application -- this requires identification of critical material parameters for a given application in close cooperation with structural design (as indicated in Section 3.4.3.1 and outlined in more detail in Section 5.7 and 5.8);

b. Development of material application -- this requires generalizations based on item (a) and should result in the definition of typical components which may serve for comparable structural and flight testing;

c. Techniques of material evaluation -- this requires establishment of generally recognized methods for testing structural components (see Section 3.4);

d. Data information system -- this requires collection, interpretation, storage, and dissemination of the vast amount of test data which are being accumulated (see Section 3.5).

3.7.2 Additional consideration has to be given to the following problems:

a. Coordination of development work -- this includes development of new materials as well as component testing and must have the goal to avoid time-consuming gaps as well as money-wasting duplications;

b. Utilization of new materials -- this includes, in addition to the problem areas shown in Section 3.7.1, the basic considerations shown in Section 3.6, with particular emphasis on anticipating and evaluating technical and financial risks in the development and application of a new material.

4. STRUCTURES

4.1 Basic Considerations

From the viewpoint of interface between materials and structures, the role of the structures engineer during the early conceptual phases of a design is of prime importance. It is during this period when vital decisions are made which determine the course of subsequent detail design. For this reason, the following considerations will emphasize those responsibilities of the structures engineer which are concerned with basic design concepts to provide strength and stiffness. Determination of basic loads and weight effectiveness are part of this concern although they may be performed in separate groups. On the other hand, refinements in analytical methods to substantiate the airworthiness with respect to static loads, fatigue, flutter, vibration, etc. are of secondary interest with respect to the present consideration because these refinements are of minor influence on basic design concepts.

The major concern in comparing various design concepts is directed toward weight reduction. It should be realized, however, that weight reduction does not depend merely on finding the optimum combination of material and structural configuration. Reference 7 indicates how all aspects of the structural system must be considered. Improvements in the fields of rational probability criteria, load alleviation and mode stabilization, analysis methods, and structural test results have to be included. Developments in these fields may result in considerable weight reduction but they are mostly beyond the scope of this report and only the relationship between analysis methods and structural test results will be considered in Section 4.5.

4.2 Methods of Analysis

Structural analysis consisted originally of a rather unsophisticated stress analysis but, in due course of time, new developments resulted in a succession of additional aspects which required major consideration:

stability -- due to the development of thin-sheet construction;

stiffness -- due to increasing slenderness of high-performance aircraft;

fatigue -- due to the growth of stress levels and service life;

rate of crack propagation and strength in the presence of damage -- due to our inability to avoid crack initiation;

creep and stress rupture -- due to sustained flight at supersonic speeds with long-time exposure to elevated temperatures.

A concise survey of the five basic mechanisms of structural action and the corresponding analytical methods is given in Reference 8. It shows clearly that a structural analysis actually consists of five different analyses, accounting for each of the following considerations:

a. Static strength, stability and stiffness of the undamaged structures;

b. Fatigue strength, i.e. time for crack initiation, of the undamaged structures;

c. Life time of a damaged structure, i.e. rate of crack propagation after damage has occurred;

d. Static strength and stiffness of a damaged structure, i.e. residual strength in the presence of damage;

e. Creep deformation and stress rupture due to long-time exposure at elevated temperature.

Most of these analyses are very time-consuming. They basically have to be conducted for each material and structural configuration. When a large number of possible combinations between materials and configurations has to be considered, the corresponding amount of analytical work to establish stresses may easily get out of hand -- just as we saw in the section on materials that the need for component testing to establish allowables may become exorbitant.

4.3 Types of Structure

Many types of configuration can be chosen for basic components of modern aircraft. Unstiffened skin, skin reinforcement by stringers or corrugations, skin with integral stringers or waffle grid, sandwich with truss core or honeycomb -- these are typical of structural developments which have taken place over a considerable period of time. Introduction of composites will open many new perspectives. Regarding our present situation, a review of applicable analytical methods and bibliography are given in Reference 9, indicating the complexities in the analysis of thin shell structures. Outspoken interaction exists between type of construction and method of analysis, and the question arises which parameters should be used as basic references.

As an example for this interaction and the difficulty to establish basic parameters, it may be mentioned that the critical parameters for a compressive member may contain modulus of elasticity or compressive yield strength in the form of E, $\sqrt{E}$, $\sqrt[3]{E}$, or $\sqrt{EF_c}$, depending on type of structure and analytical method. Such analytical considerations are in addition to other structural aspects which cannot easily be put in parametric form,

e.g. joint efficiency -- where fatigue considerations make it desirable to have a minimum of splices while fail-safe considerations call for a good number of them.

As another example it may be mentioned that structural failures during recent years much too frequently occurred in unsuspected places. It appears that techniques for overall analysis are well developed, yet these failures originated from special local conditions which had not been sufficiently established by test or detail analysis. With the introduction of more new materials and new structural configurations, this "risk of the unknown" may assume still greater importance. It represents an aspect which by its very nature does not lend itself to an approach in form of structural parameters but rather requires a systematic process of qualitative considerations.

From the structural viewpoint, a typical parameter for a certain type of panel in compression may be, for instance, $E^{.4}/\rho$. From preceding and subsequent considerations it can be seen that a parameter must be used in conjunction with other considerations which have to be identified for each component and, as a result, the importance of structural parameters by themselves may be greatly reduced.

Basic material parameters have frequently taken the place of structures parameters for purposes of comparison during the early design phase. Specific tensile strength (F_{tu}/ρ) and specific modulus (E/ρ) have been the most commonly used basic parameters in spite of a general realization that ultimate tensile allowable has lost most of its significance due to the importance of fatigue and fracture mechanics, and that the modulus has to be modified by an exponent. Many other parameters can be considered. This question of basic parameters brings out the full complexities of the interface between materials and structures, and the discussion will be continued in Section 6.

4.4 Selection of Structural Configuration

During the design process, the structures engineer is concerned with two different aspects: Firstly, when he selects a structural configuration he has to look at overall problems and make basic decisions. Secondly, when he analyzes the airworthiness of the final design he has to take responsibility for each structural detail and face the consequences of his earlier decisions.

Available methods of analysis incorporate considerable refinements. These are, however, of not much help for comparing various types of structures during the early phases of design. To understand this phase, it will be necessary to consider the process which is generally used for the selection of a certain type of structure. A typical approach looks as follows:

The first step is taken in close cooperation with aerodynamics and design and consists of establishing operational and environmental conditions, including combined loads, critical temperatures, etc.

The second step consists of selecting cross-sections or box segments which can be considered typical of the given geometry and operational and environmental conditions.

The third step consists of determining the structural members required for a typical cross-section or box segment, comparing various materials and structural configurations, and developing a structural concept which results in minimum weight.

The third step includes two different aspects:

a. Actual loads and stresses have to be calculated - at this early stage usually by rather elementary methods and simple computer routines;

b. Allowable stresses have to be established for typical components -- usually requiring a combination of experimental and analytical methods, and frequently based on estimates at this early stage.

This second aspect of establishing allowables is time-consuming and expensive. For structures in compression, allowables refer basically to compressive stability which depends on the dimensions of the structure. If often requires structural testing which is in addition to the fundamental material testing described in Section 3.

Based on this type of data, the specific weight for various types of structure and material can be plotted as a function of the allowable end load. The process of selecting a structural configuration may conveniently start with such a set of graphs. It will indicate, of course, that highest weight effectiveness requires different materials or structural configurations for different end loads and different environmental and operational conditions. Many iterations will generally be necessary to arrive at a satisfactory solution.

It should be borne in mind that the preceding description of a typical method for selecting a structural configuration for compressive loads is only a part of the total picture. For structures in tension, fatigue allowables are usually critical but they can be established only when design details and corresponding stress concentrations are known. Until then, estimates have to be used. This means that the choice of a structural configuration for tensile loads has to be based to a large extent on previous experience with similar structures. Justification can be established only by detail design and detail analysis -- much farther downstream in the development process.

The same is true with respect to establishing the airworthiness of a damaged structure, as mentioned in Section 4.2. Its rate of crack propagation and residual strength also depend on design details which are still unknown during early design phases and can only qualitatively be considered.

In addition to allowable loads, bending stiffness EI and torsional stiffness GJ must be considered. These data refer to overall stiffness of the structure for purposes of flutter and vibration analysis and they can be determined during the early design phases. The result may be, for instance, that a skin-stringer combination which is more weight - effective in compression has to be abondoned in favor of a sandwich construction giving higher torsional stiffness.

The preceding discussion points out a rather interesting observation: During the selection process, a well-defined analysis for purposes of comparing various designs can be conducted for compressive stability and for stiffness. Most other considerations require assumptions and judgment because at the time when basic decisions regarding materials and structures have to be made, not enough information on detail design is available to make full use of analytical methods.

It becomes apparent that concern about controlling parameters which identify a structural configuration for analytical methods should be subordinated to more fundamental considerations regarding our approach to structural design and analysis. Judgment and experience of the structures engineer are needed as a controlling input during the decision-making process. No systematic approach, however, has been developed in the field of structural analysis to introduce judgment and experience. Any attempts toward clarifying this field deserve full attention, and the discussion of this aspect will be continued in Section 6.

4.5 Analysis Methods and Structural Test Results

The relationship between analytical methods and test results is of particular interest for the interface of materials and structures. Agreement between analysis and experiment is the basis for our confidence in the integrity of a structure. Frequently, however, there is considerable scatter between test data and besides, different analytical methods may be available for the interpretation. Corresponding uncertainties often result in conservative designs and weight penalties. The answer has to be found in structural test programs which go beyond the scope of the structural tests mentioned in Section 4.4.

Reference 10 singles out this problem and gives several characteristic examples. Basic improvements in strength prediction methods can be obtained by systematic programs which investigate the development of allowables on structural components in conjunction with applicable methods

of analysis. Individual programs may run over several years and cost millions of dollars because they have to be very comprehensive. Their economic feasibility, however, can be easily established.

In many cases expenditures for testing will result in significant economic advantages on a single production model and the cost will be borne by the manufacturer. In other cases a problem may have industry-wide significance and should be relegated to a research agency. Much additional work and large-scale planning is necessary in this field.

4.6 Structural Optimization

As the number of possible combinations for material and structural configuration increases, the selection process described in Section 4.4 gives no assurance whether the chosen combination is close to an optimum solution. The goal of the structures engineer is, of course, to develop an optimum structure. This is an all-encompassing task, and much effort is being extended toward developing methods for structural optimization. References 11 and 12 indicate the magnitude of this effort, give a concise survey of the subject, and include an extensive bibliography. Reference 13 gives a brief description of the state of the art with respect to aircraft structures.

Fundamental difficulties exist in the fields of mathematical programing and search methods. For this reason, presently available methods form only a first step toward structural optimization and are more properly categorized as automated structural design. Computer programs have been developed to determine section properties resulting in minimum weight for a set of applied loads and for chosen constraints in form of allowable stresses and displacements, minimum gages, etc. -- but only for a given structural concept and configuration.

No method for a systematic selection process between various structural concepts is visible at present nor has there been any effort to include complex cost considerations or engineering experience. Solution of these problems is a pre-requisite for structural optimization and any estimates regarding the time required for future developments are obviously speculative. Considering the accomplishments of the past ten year, however, there is reason to anticipate that significant progress will be made within approximately a decade - perhaps earlier, perhaps later.

It should be pointed out that the terms "structural optimization" and "optimum design" are frequently employed quite loosely in the literature. First of all, it is always necessary to specify whether optimization takes place with respect to weight, cost, or some other quantity. Overall optimization has to be based on a known relationship between these quantities. Beyond this, present optimization methods are based on theoretical considerations, assuming well-defined parameters. Real-life

conditions, however, are frequently not so clearly defined.

In the preceding discussions we saw the important role played by structural configuration, material application analysis and material evaluation techniques. Further inputs from the design viewpoint will be discussed in Section 5. All these considerations in different fields eventually need to be incorporated in structural optimization. It may be anticipated that these complexities will necessitate a close man-computer interaction rather than a fully automated program. In any case, however, much clarification will have to be obtained regarding the fundamental thought process involved in structural design.

4.7 Summary of Problem Areas Regarding Structures

From the viewpoint of interface between materials and structures, the root of the problems in the field of structures may be found in the recognition that our well-advanced analytical methods are only of limited usefulness during the early phases of developing a design concept. A high skill in the application of analytical methods has become traditional for the structures engineer, but he has not yet developed a systematic approach toward surveying the many possibilities of failure and becoming aware of possible surprises lurking beyond the well-defined region of established analytical procedures.

This results in a pervasive task. During the early design phase, the emphasis will be on applying previous experience toward avoiding future difficulties. During the final phase of analytical substantiation, the emphasis will be on continuous probing whether analytical methods are in full agreement with available experience.

The following points are pertinent in this context:

a. During the early process of selecting a structural configuration, stiffness and compressive strength can be established by well-developed analytical methods; tensile strength as determined by fatigue can be established at this early time by analytical methods blended with experience; most other basic mechanisms of structural action can not yet be put in quantitative form due to a lack of available details and must be evaluated qualitatively based on judgment and experience.

b. This indicates that during the early design phases, when the basic decisions regarding material and structural configuration are made, the structures engineer must supplement analytical methods by reliance on design experience.

c. Design experience covers a wide field which has to be narrowed down to those aspects which affect the selection of material and configuration from the structural viewpoint. Significant questions regarding anticipated types of failure, uncertainties about allowables or methods of analysis, necessary test programs, important design details, etc. have to be considered and potential problem areas have to be identified.

d. The resulting implications regarding evaluation and accumulation of experience will be discussed in Sections 6 and 8. From the viewpoint of the structures engineer, the fundamental aspect consists of the need to find a systematic approach toward these questions as a basis for evaluating complex structural designs.

e. The structures engineer will also have to play an important role in the development of new design concepts for new materials.

f. A further field for continuous vigilance in connection with new materials and structural configurations is the coordination of analytical methods with structural test results as discussed in Section 4.5.

5. DESIGN

5.1 Basic Considerations

It may be worthwhile to begin with some general thoughts which are quite pertinent to our subject. Any engineering design is concerned with all aspects of a project, from original concept to final hardware. Whether the design consists of a small fitting or a major aircraft project and whether the designer is a detailer or a project engineer -- the difference is only in degree, and in each case the design engineer has to take full responsibility for his product.

This responsibility extends both vertically throughout the service life of the part he has designed, from cradle to grave, and horizontally into a coordination with all other aspects of the system. In this sense, the functions of designer and systems engineer are essentially identical, no matter what the title is.

Yet the term systems engineering and the high esteem in which it is held, signify our general trend toward specialization. This trend is clearly visible in the emphasis on analytical techniques in engineering education as well as in the prestige accorded to the analyst. It is a trend which has been detrimental to cultivating those qualities which are the very essence of the good designer: creativity, engineering perspective, instinct for team work, appreciation of synthesis as well as analysis.

As a consequence, it has been difficult for industry to attract promising college graduates into design and also to keep experienced designers from moving on into more prestigious positions. Reference 14 gives an eloquent description of the situation. There seems to be a slowly growing awareness of the importance of this problem but no early remedy can be expected.

These background considerations will have some bearing on the overall picture. The airframe designer has final responsibility not only for the choice of material as selected by the materials engineer and the airworthiness of the structure as analyzed by the structures engineer, but also for overall function, reliability and development risks as well as for cost of material, production, and maintenance, and he has to balance all these considerations against each other. Therefore, the designer will ultimately be the coordinator of the problems which are encountered regarding interface of materials and structures.

For the purposes of this report, the functions of the structures engineer and other specialists will be considered separately from those of the designer although, particularly during the early design phases, there is some overlap. For instance, the structures engineer may assume some of the responsibilities of the design engineer because the border lines are flexible.

5.2 Parametric Studies and Design Proposal

Any aircraft design starts with a definition of performance requirements and continues through the iterative process of parametric studies. Basic parameters like payload, range, speed, wing loading, thrust loading, etc. are chosen and varied systematically in order to arrive at an optimum layout.

Structural weight is of major importance during this process and depends on one hand on the interface of aerodynamics and structures and on the other hand on the interface of materials and structures. Both these aspects have to be considered during the early design phases and there is some similarity between them as both involve optimization problems which have not yet been solved and both are usually approached in a somewhat informal process.

At this early stage of design, however, no accurate estimate of structural weight is possible and the designer has to rely on statistical data of similar aircraft and on the experience of structures and weight engineers to arrive at an educated guess. Depending on the given specifications, reduced structural weight may result in smaller propulsion and fuel requirements and in resizing of the aircraft, i.e. an additional cycle in the iterative process.

These considerations with regard to parametric studies and resizing of the aircraft are of fundamental importance. Yet from the viewpoint of interface between materials and structures, they are of the same kind but of less thoroughness as subsequent considerations which have to be submitted for the later phase of the design proposal. Parametric studies take place under the partly frustrating, partly inspiring conditions of frequent changes in early design concepts and of large gaps in available data which have to be bridged by judgment and experience. In terms of Section 3.4.3.1, early phases of parametric studies represent a screening process while the design proposal incorporates the results of a selection process.

The following sections, although basically applicable to earlier parametric studies, consider the particular situation as it exists during the process of selecting material and structural configuration for the design proposal. It is at this time when full attention must be given to the interface of materials and structures and all fundamental design decisions are made. Subsequent design details should consist mostly of refinements along the line of reasoning which led to the design proposal.

After the viewpoints of materials and structures engineers were considered in Sections 3 and 4, additional consideration will now be given to the viewpoint of the design engineer. This will include value engineering as an additional field of specialization.

5.3 Basic Responsibilities of Designer

The structural designer has to accomplish a creative process which requires a broad technical background. During the initial design phase he starts out with a general goal, considers various concepts by which it may be achieved, can not afford to overlook any possibility which might hold promise nor risk being side-tracked along time-consuming and devious bypaths, has to evaluate the advice of specialists, has to make many design decisions and has to consider the problems from a wide perspective.

During the final design phase, he is directly responsible for all the details which make the difference between a good and a poor design, including tolerances, manufacturing considerations, time schedules, etc.

During the whole process the design engineer has to make full use of the specialized knowledge and experience of structures, weight, materials, process, production, value, and systems engineers and has to coordinate their efforts as he compares alternate design studies and proceeds with the detail design. The problem of interface between materials and structures pervades most considerations throughout the process of structural design. The important role of the designer in the decision-making process will be discussed in Section 6.

5.4 Cost Effectiveness

Cost effectiveness has only recently assumed major importance in aircraft design. Previously the main concern consisted of designing a part in a given material for minimum production costs. Now, with an ever increasing number of materials available, the problem consists of determining the cost effectiveness of various combinations of material and structure for the total system. This includes costs of material, manufacturing, maintenance and operation with due consideration for the cost of design, development, test and evaluation. An additional very important and hard-to-predict influence is quantity of production. Even questions of policy may enter regarding the relative importance of purchase price and operating cost.

Considerations of cost effectiveness are now usually relegated to specialists in value engineering. The general approach to the problem is well described in Reference 15 and unclassified parts of this reference will be summarized briefly in the following paragraphs.

The prediction of relative manufacturing costs for alternate materials and structural configurations always poses a major problem. Manufacturing costs of a state of the art design can serve as a basic cost reference. Starting with this reference, effects of new materials and different structural configurations on production costs can be expressed in terms of cost factors.

Manufacturing operations are broken down to indicate the relative cost of each operation for each material and the distribution of manufacturing operations for each production element. Proper combination of these factors with due consideration for relative weights results in "Workability factors" which express the ratio of manufacturing labor hours between new and reference materials. The accuracy of such cost data depends, of course, on the availability of detail data, and the procedure requires a considerable amount of detail work which can be put in form of a computer program.

Design, development, test and evaluation (DDT & E) costs are separated from production costs, and each is broken down into a number of subgroups. Statistical data based on past experience can be put in form of equations with typical design parameters, but they can be applied only to similar types of construction.

The additional step of predicting DDT & E costs for an alternate design have to be based on manufacturing material and labor, initial engineering and tooling, sustaining engineering and tooling, and quality control.

Total system costs should include investment costs, incl. spares and initial training, as well as operating costs, incl. recurring spares and depot maintenance. Another very major consideration is maintenance cost. This includes corrosion control and it is shown in Reference 16 that this aspect may play a dominant role, for instance, in a cost comparison between aluminum and titaniam for Navy aircraft.

Another aspect of cost effectiveness is also considered in reference 16. Assuming constant range and pay load, aluminum parts are sequentially replaced by titaniam, investigating difference in weight and system costs at each step. Those parts where the advantages of titaniam substitution seem most obvious are replaced first, and it can be shown that system costs in a given case reach a minimum when about 30 to 60 percent of the aluminum is replaced by titanium.

A further consideration which cannot easily be assessed from the viewpoint of cost effectiveness concerns damage tolerance and repairability. Damage may be due to fatigue cracking, accident, or military action, and probability of occurrence depends on type of service.

These cost considerations were shown in some detail in order to indicate the complex manner in which the choice of material and structural configuration influences overall costs.

5.5 Cost-Weight Effectiveness

Weight effectiveness has always been a dominant consideration in aircraft design and it is inseparably connected with the responsibilities of the

structures engineer. The standard analytical approach, which forms the present basis for weight effectiveness, was discussed in Section 4.4. Future possibilities in connection with new methods in structural optimization were indicated in Section 4.6.

As an additional consideration, actual conditions must be thoroughly compared with theoretical conditions before new materials or different structural configurations are introduced. Otherwise, much of a theoretical weight saving might be lost due to secondary reasons like joints, access holes, manufacturing limitations, etc.

Weight considerations include two aspects because a minimum-weight structure must satisfy both airworthiness requirements and cost effectiveness. The methods to meet airworthiness requirements were discussed in Section 4. Corresponding methods to establish cost effectiveness were considered in the preceding Section 5.3. Both these aspects have to be brought together by establishing the value of weight saving which forms the basis of cost-weight effectiveness.

The value of weight saving varies during the design process. In the early stages, when design concepts are still flexible, weight changes will result in resizing of the aircraft. At a given pay load, range, and speed, a reduction in structural weight means smaller propulsion requirements and smaller fuel loads and the resulting reduction in gross weight may be several times larger than the original structural weight saving.

This multiplying effect is expressed by a "weight growth factor" which is determined by a parametric study including configuration, performance, and weight analyses and is particularly important for trade-off studies in early design concepts.

After the aircraft configuration has been frozen, weight saving assumes a different value which may have to be determined from gain in pay load or decrease in operating cost or may also be influenced by secondary factors, like having to meet guaranteed weights and trying to avoid penalties.

The determination of the value of weight saving involves complex considerations and a decision is frequently made on a high level of management. A reliable value requires clearly defined conditions, and typical values are of the order of several hundred dollars per pound per aircraft. The implications regarding additional engineering efforts which can be spent on a large-production order are obvious, and clear guidelines must be established for making design decisions.

Cost-weight effectiveness combines weight data with cost data, using the value of weight saving as a trade-off. For various combinations of material and structural configuration, the cost ($\$/ft^3$) and weight ($\#/ft^2$) must be

established. Various graphical representations can be used to plot these data so that the best cost-weight effectiveness is obtained at a given value of weight saving. Such considerations are, of course, of basic importance for the choice of material and structural configuration.

5.6 Qualitative Considerations and Trade-Offs

Cost-weight effectiveness, with all its fundamental importance for aircraft design, does not make allowance for a great many design considerations which may be equally or even more important. Some of the basic considerations were indicated in the discussion of materials and structures in Sections 3 and 4. Many more detail considerations emerge as a material is applied to a structure and considered from the designer's viewpoint.

When the designer determines design details, closest coordination with materials and structures engineers is essential. As previously discussed in Section 3, many of the material characteristics and structural allowables can be established only in conjunction with detail design after component testing. Estimates have to be made at the time of alternate design studies and they may include the following kind of considerations:

- Fatigue (influenced by local stress concentration resulting from detail design);
- Crack propagation (influenced by local stress level and detail design);
- Structural joints (number of fasteners, type of welding, etc.);
- Fail-safe characteristics;
- Heat treatment (incl. need for stress relief);
- Finish (incl. need for shot-peening);
- Producibility (incl. available equipment and know-how);
- Inspectability (incl. manufacturing and service);
- Maintainability (incl. corrosion problems);
- Repairability (incl. fatigue cracks, accidental and military damage);
- Growth potential;
- Equipment accessibility.

Some of these items can be evaluated quantitatively based on weight or cost, but most require qualitative evaluation based on judgment and experience. In this case it is necessary to be as explicit as possible about the method of qualitative evaluation. Length and type of experience with the same or similar items, aspects of confidence and of concern regarding the development of the item, necessary testing, schedule for final acceptance -- all these considerations are subject to individual judgment

but they can be made visible when broken down into such discrete elements.

A break-down like this can remove the irrational and mystical aspects from the somewhat vague concepts of judgment and experience. Differences of opinion will remain but they are narrowed down to better-defined fields which can be discussed on a rational basis and finally put into a system of trade-off factors.

During the phase of alternate design studies leading up to a design proposal, the designer has to be aware of all the implications of cost-weight effectiveness and trade-offs. The process of putting qualitative considerations on a quantitative scale for trade-offs requires much additional thought but it is of great importance for the choice of material and structural configuration. Sensitivity considerations enter here as also in other places.

Another field of great fundamental importance, which was mentioned in Section 3.4.4 as joint responsibility of materials, structures, and design engineers, is material application analysis. This will be discussed in the following sections.

5.7 Material Application

The term "material application" is often employed somewhat loosely and several connotations can be found. For the purposes of this report, the important aspect is material application analysis which may be defined as follows: Material application analysis is concerned with determining those material properties which are critical when the material is applied to a given component.

The need for determining material properties under the proper environmental and operational conditions was discussed in Sections 3.2 and 3.3 as a responsibility of the materials engineer. Two questions were left unanswered: how are environmental and operational conditions established and what are the critical material properties?

Determining the proper environmental and operational conditions and incorporating their basic aspects in the design proposal, represents a fundamental part of any aircraft design. Operational conditions are determined by establishing basic loads -- a fundamental process which has been developed over decades. Environmental conditions have become important only recently, but they can be established by systematic considerations and the main difficulty is to make sure that no potentially important aspects are overlooked.

The situation is different, however, when it comes to the critical material properties which correspond to environmental and operational conditions. Until a few years ago this was a fairly simple question which could be

decided in an off-hand manner by the experienced structures engineer. Yet due to the increasing complexities of high-performance aircraft and the increasing number of available materials, this formerly simple question has developed into a sizable problem.

No systematic approach has been developed yet for introducing the critical material properties under complex conditions into the design process. The seemingly simple answer to consider all properties under complex conditions would run into prohibitive time and cost requirements. Instead, it has become common practice to select critical material characteristics for each case individually by empirical methods and refine the process as additional details of the design may develop.

The principal difficulty is that a multitude of influences may contribute to final failure -- stresses, load cycles, temperatures, corrosive conditions, time, etc. It is hard to determine which combination of environmental and operational conditions and material properties is particularly critical and there always remains the danger that one of the critical conditions may be overlooked in the analysis.

One approach to this problem is shown in reference 1 as described in section 3.4.3.1. It consists of formalizing the heretofore informal and empirical process of requiring an increasing number of data on material characteristics as the design proceeds.

> As a first step, parametric studies for comparison of various concepts require only a few properties for screening of materials;
>
> the second step, consisting of the design proposal, has to be based on trade-off considerations which require many additional properties for selection of the proper material;
>
> the detail analysis, finally, requires the full set of material characteristics for design data.

Such a systematic process provides for clarity and it facilitates checking -- two very important aspects in view of a complex situation. It requires, however, clear identification of the corresponding properties for typical components.

An additional need, namely to identify the available testing techniques corresponding to established design criteria, was outlined in the second step of section 3.4.2.2. Reference 1 allows for this although no further work was done along this line. It will be the responsibility of materials engineers to supply the necessary information.

*   *   *

Tabular recording of material characteristics for each component, as proposed

in reference 1, is a significant step in analyzing material application. It incorporates an approach which had been developed previously in a somewhat different form and in considerably more detail by proceeding along a similar line of thinking. This will be considered in the following section.

5.8 Basic Shapes

The concept of basic shapes is discussed in reference 17 and will be summarized briefly in this section. It refers to basic components which exhibit recurrency or commonality with regard to configuration, functional characteristics, and basic problems. Typical examples are lift surface panels, pressurized cylinders, leading edges, wing spars, canopies, fasteners, etc.

This component-oriented concept was developed because the present system-orientation of applied research is impeded by narrow time limitations and specific requirements. System-orientation frequently precludes systematic development and perfection due to the need for an immediate solution of a particular problem.

A component-oriented approach, however, generates an awareness of essential characteristics, identifies basic requirements, and provides for improvements through a systematic development program. It was originally conceived from the viewpoint of manufacturing technology but it is just as useful from the viewpoints of material application and design. In each of these fields, there is a great need to clarify the essential requirements, to provide an open door for new ideas to identify problems which have to be solved by research programs and to make sure that a systematic evaluation process is followed.

The concept of basic shapes excludes the definition of specific materials, designs, and manufacturing methods. It provides data and supporting information solely on requirements. The means to achieve these requirements do not pertain to the definition of basic shapes and are left to the ingenuity and systematic evaluation of the designer.

The heart of these requirements is expressed in specification data which may be shown in five parts for each basic shape. Choosing a fuselage shell for illustration of some of the details which vary for each component, these five basic parts are:

> Environment (incl. temperature and time, chemical, and radiation influences);
>
> Basic configuration (geometry, range of dimensions, assembly requirements, discontinuities, incl. sketches and numerical data);

Basic functional requirements (incl. typical values of specific strength, stiffness, and unit weight);

Specific functional requirements (incl. specifications and data on fatigue life, acoustic fatigue, stress corrosion, thermal stress, thermal strain, creep, and impermeability);

Applicable material properties (incl. specific compressive and tensile yield allowable, specific modulus, specific tensile allowable, fracture toughness, fatigue strength, creep, oxidation resistance, etc.).

From the viewpoint of interface between materials and structures, such an approach is fundamental for material application analysis and also very helpful to clarify qualitative considerations and trade-off factors mentioned in Section 5.6. It also defines component requirements for material development and points out the need for a systematic consideration of a great many details.

This work was started in 1967 but has not been continued since. Continuation of a program along these lines would form an essential step toward establishing a solid foundation for material application Special consideration should be given to the selection of components so that they can serve as a representative basis for comparison of material and structures.

The discussion in section 3.4.3 indicates that reference 1 comes to conclusions regarding material application which coincide with those of reference 17. Reference 1 makes the distinction between the three phases of screening, selection, and detail design which represents a very useful contribution. Otherwise, reference 17 goes into considerably more details and the three phases from reference 1 can easily be incorporated into the approach used in reference 17.

5.9 Summary of Problem Areas Regarding Design

From the viewpoint of interface between materials and structures, the main problems in the field of design are closely connected with the task of the responsible designer. He is at the center of the effort which is required to find the optimum combination between material and structural configuration. He has to evaluate and coordinate the work of specialists in the fields of materials, structures, production, and value engineering, has to incorporate it in his structural design, and has to take the overall responsibility. The following problems are considered to be particularly significant:

a. A large gap has developed between the fundamental importance of the designer's task and the apparent lack of educational preparation for his specific responsibilities. Promising students are

shunted toward dominantly analytical work, and college curricula have been generally weak in those fields which are important in the education of a designer -- namely combining analytical methods with creativity, practical judgment and overall perspective. Only recently some first steps toward a remedy of this situation have been taken.

b. In addition to having a solid educational preparation and an open mind for new approaches, the designer leans heavily on experience. The basic considerations about design experience, which were summarized from the viewpoint of the structures engineer in Section 4.7, are also applicable to the designer after minor modifications.

c. Material application analysis provides a basic and particularly important meeting ground for materials, structures, and design. The efforts described in Section 5.8 form a good foundation for systematic work in this field. Extension of this type of work is fundamental for any application of new materials to aerospace structures.

d. Qualitative considerations and trade-off factors are at the very core of structural design. Much work has to be done in this field and some basic aspects will be discussed in the following Section 6.

6. CONTROLLING PARAMETERS AND TECHNICAL DECISION PROCESS

6.1 General Considerations

In the introduction it was stated that the purpose of this report is not only to give a systematic survey of fundamental problems but also to pay special attention to the line of thinking which leads to the establishment of controlling parameters required for structural design. Controlling parameters can be established only in clearly defined systems. Such systems exist for structural analysis of given types of components in compression, fatigue, etc., and it is standard procedure to combine material properties with structural dimensions in order to form characteristic parameters.

For the solution of the typical design problem, however, which consists of finding an optimum solution with due consideration of material properties, structural configuration, available methods of analysis, production techniques, processing requirements, time schedules, cost of manufacturing and maintenance, etc., no clear system exists. A first step must necessarily consist of a clarification of the thought and decision process leading toward a structural design. Much of this has been obscured by general reliance on experience, judgment, and intuition -- all of which are interwoven and rather ill-defined. With increasing complexities, the limitations of the traditional intuitive approach to the design problem are becoming painfully obvious and the need arises to consider the fundamental aspects of the problem.

6.2 Present Situation

A typical approach for finding a first approximation of member sizes was discussed in Section 4.4. This serves as the beginning of an iterative procedure between

a. tentative design, based on evaluation of basic parameters and analytical methods;

b. stepwise refinements, taking into account considerations of manufacturing, maintenance, cost, reliability, etc. as well as additional test data and more detailed methods of analysis.

This procedure is applied to the various materials and configurations which are under consideration during early design phases. It is concerned with the very essence of the interface between materials and structures and of structural design. The line of thinking and the technical decision process which take place at this time will have to be clarified to provide for a systematic approach and some of the fundamental aspects will be considered in the present report as a basis for further work in this field.

Some basic work has been done along these lines in fields of special interest, like value engineering and cost-weight trade-offs. Questions of manufacturing, maintainability, etc. can be compared on a cost basis and also the value of weight can be clearly expressed in terms of dollars when a reference basis has been established.

This leads toward using cost-effectiveness as a basic parameter for comparison -- a concept which is held in low esteem by the engineering community. The reason for this apprehension is the fear that qualitative values, which are so often decisive in design problems, cannot be expressed in terms of cost. Yet a common denominator has to be found in order to compare different varieties and the eventual answer appears to be in the field of cost effectiveness -- after the sinister meaning has been removed from the term by including qualitative values.

The present situation may be described as a state of transition. There is a general awareness of not being able to express the qualitative and somewhat intangible aspects of the traditional design procedure. Beyond this, the magnitude of the optimization problem which the interface of materials and structures presents, has been recognized. Considerable efforts are being extended toward solving its mathematical aspects, but very little has been done about establishing basic principles and data which are required in the fields of materials, structures, and design and which were discussed in Sections 3, 4, and 5.

The main problem consists of recognizing and organizing the large amount of work which is necessary to establish a solid foundation in the fields of materials, structures, and design. Such a foundation is necessary for clarifying any work regarding interface of materials and structures in the near future as well as for having prerequisite input data for structural optimization in the more distant future. It involves work which requires considerable leadtime. There is a distinct possibility of drifting into a highly embarrassing and bizarre situation: having sophisticated optimization methods available in the foreseeable future and simultaneously lacking the most basic input data on a completely elementary level.

6.3 Specific Problems

The preceding discussions indicate that in the field of materials there are still unsolved problems regarding data acquisition and application which are of a straight-forward engineering nature, as shown in Section 3. In the fields of structures and design, however, as shown in Sections 4 and 5, the basic difficulties of an engineering nature have been recognized and are in the hands of specialists who can be expected to arrive at solutions in due course of time. Yet there are other unsolved problems on the borderline of the engineering domain which are of a type with which the engineer is not very familiar and which become important for the interface of materials and

structures. The fields of qualitative considerations and trade-offs, evaluation of experience, risk evaluation, and the technical decision process are of particular concern.

Qualitative considerations and trade-offs were considered in Section 5.6 -- without arriving at clear results. What has been done intuitively in simple systems has to be translated into a systematic approach for complex systems. An important first step toward a solution, as suggested in Section 5.6, consists of breaking up qualitative considerations into small discrete elements, assigning a quantitative value to each, and exposing this process to full visibility in order to offer a challenge to the subjective inputs which are necessarily based on experience and judgment. An approach along these lines is beginning to be used informally in the aerospace industry. This should help to direct attention toward this subject and gradually to clarify the situation because finding reliable quantitative expressions for qualitative considerations is the prerequisite for establishing trade-off methods.

Evaluation of experience represents another subject of very basic importance. We lean heavily on it in all considerations of interface between materials and structures. Before we can evaluate experience, we have to accumulate it and this aspect will be discussed in more detail in Section 8. For the evaluation, however, it must be realized that experience in itself is meaningless unless we utilize it. A limited amount of experience can easily lead to narrow prejudice and it is only the judicious evaluation of experience which becomes valuable. This evaluation of experience leads to engineering judgment which is an instinctive process for the good designer and which has to be clarified in order to incorporate it in a systematic approach.

Risk evaluation has to be applied to many aspects of design, particularly to any new developments in the fields of materials and structural configurations. Both technical and financial risks have to be considered where the technical risks can be expressed as quantitative values in terms of eventual cost. Probability of success, cost of failure and alternate possibilities have to be included, and methods developed in operations analysis can be used to a certain extent.

The technical decision process which results in the final design is the most essential part of the design procedure. It has to include basic technical aspects like material properties, material application, structural analysis, cost considerations for materials, development, manufacturing, and maintenance. Beyond this, it also has to identify, clarify, and incorporate more obscure regions of the traditional engineering discipline like qualitative considerations, evaluation of experience, and risk evaluation. All this has been done intuitively by the experienced designer as long as he could oversee the implications of the problem, but with increasing complexities the limitations of this procedure have to be recognized. As a consequence, it will be necessary to probe into those aspects of the design process which have

been somewhat intangible, clarify them, and develop a clear procedure for the technical decision process. This will result in the establishment of controlling parameters.

6.4 Summarizing Remarks

It is a sizable task to arrive at a clarification of the thinking process in the fields of qualitative considerations, evaluation of experience, and decision-making. Engineers in the fields of materials, structures, and design have been occupied with many problems of a purely technical nature and are just beginning to become aware of the importance of these overall problems. It will require some time until a generally accepted procedure can be expected. In the meantime, some steps can be taken which point in the right direction and may contribute toward a final solution. The following sections will consider the roles which the relationship between manufacturer and customer and the accumulation of experience can play in this respect.

7. MANUFACTURER AND CUSTOMER

7.1 Role of Customer in Aircraft Design

Up to this point, the interface of materials and structures was discussed from the viewpoint of the manufacturer whose objective it is to produce an optimum aircraft. Now it will be necessary to look at the same questions from the viewpoint of the customer whose objective it is to procure an optimum aircraft.

For military aircraft, the customer is simultaneously procuring as well as licensing agent. As a procuring agent, he is particularly interested in evaluating competitive proposals. As a licensing agent, he has to ascertain that airworthiness requirements are satisfied when the aircraft goes into service. In both cases he is in close relationship with all engineering aspects of a project. With regard to interface between materials and structures, however, he has a basic interest in the decisions which lead up to the design proposal.

The situation is different for civil aircraft. The FAA as licensing agent is interested purely in airworthiness aspects. The purchaser, on the other hand, usually does not have much influence on design decisions and is more interested in the cost of maintenance and operation of a given aircraft. For these reasons, this discussion will be limited to the role of the customer in the procurement of military aircraft.

7.2 Basic Aspects of Design Competition

The design competition among several manufacturers is based on the specifications which are prepared by the military customer in connection with the request for proposals. These specifications are a voluminous document and are explicit with respect to many detail requirements. A proposal submitted in response to the customer's request typically contains dozens of volumes of detail information and represents a major effort by an aerospace company involving several million dollars of expenditure. Evaluation of this information by the customer forms the basis for awarding the contract.

There is no methodology available for this evaluation process and the complexities of the situation must be appreciated. As we have seen, in spite of much analytical sophistication, a design incorporates much intuitive judgment. When it is evaluated, a different set of values is generally used for judging because no widely accepted standard of values exists. Each individual may use a different approach and different assumptions, each may justify his conclusions by quoting certain examples, and each may defend his conclusions in good faith. The problem consists of making the transition from faith to facts.

This problem can be identified as existing solely in those regions where we depend on individual experience and judgment. There are no difficulties whenever analytical methods and quantitative values are available. Yet we have no methodology for evaluating forecasts which incorporate new developments, details which may have caused trouble under certain conditions in the past, or many aspects of the risk of the unknown. The approach, for the time being, will have to be along the same line as shown in Section 5.6. By providing visibility for the decision-making process and dividing it into clear steps, it can be made more accessible to reasoning.

Much of the problem is concerned with communication between customer and manufacturer. What is the best way to select and present essential information? How can the customer recognize a thorough effort without being inundated with a maze of details? Which parts of a design proposal are fundamental and which disputable details may be verified in time or changed without major consequences? How can different types of experience be evaluated? What is the role of trade-off values?

There is no easy answer to such questions. As a general guideline, it will be necessary for the customer, as he writes the specifications, to put himself into the shoes of the designer while the designer, as he submits his proposal, must put himself into the shoes of the customer. This may help each one to anticipate and understand the problems of the other.

Any of the preceding questions may be answered in different ways and may cause misunderstandings. Good communication between customer and manufacturer is necessary to make sure that both are thinking along the same lines. Frequently the major part of a typical proposal for a structural design consists of analytical work and does not discuss some of the qualitative considerations because the manufacturer does not know how they may enter into the evaluation procedure. In spite of voluminous specifications by the customer, the manufacturer will always have questions of interpretation. On the other hand, no matter how comprehensive a proposal by the manufacturer is, the customer will always have additional questions.

Under these complex circumstances, it can hardly be expected to arrive at a perfect set of specifications. Any modification of existing specifications is a major undertaking. Perhaps additional guidelines based on previous experience may facilitate interpretation in some cases.

7.3 Additional Aspects of Design Competition

Throughout the considerations of this report it has been apparent that structural design has entered a period of transition toward new and more sophisticated methods. The implications of this situation are quite staggering and a solution for the inherent difficulties regarding interface of materials and structures is beyond the capabilities of single manufacturers. Much

coordination and support of individual efforts is required and the military customer is in a powerful position to influence and direct developments. He can provide guidance and encouragement, and establish fundamental policies.

The specifications for a design competition can be a particularly important instrument with respect to development of hardware and solution of interface problems between materials and structures. The following aspects deserve special attention:

a. Application of new materials in aircraft structures involves risks which have to be balanced against potential gains. Both have to be viewed in terms of the specifications for the design competition which usually provide for a fixed-price competitive situation with constraints on cost and time schedule making it almost prohibitive for the manufacturer to incur the uncertainties of introducing new materials and new production methods.

   The specifications, however, may as well be written to implement a different procurement policy more favorable to the development of new material application. For instance, in addition to a state of the art design at the time of the competition, an alternate solution may be specified for some components based on the expected state of the art at the time of introduction into service. Such an alternate solution would provide for a realistic comparison at moderate cost without risk. Besides, specifications may call for identification of potential improvements or may given commensurate incentives for new developments.

b. Specifications can also help in clarifying new concepts. It was seen in Section 6 that there is no accepted procedure with respect to design decisions and that a clarification in this field is important to both customer and manufacturer. Some valuable basic information could be gathered if the specifications would encourage the manufacturer to provide visibility for the line of thinking which leads to important design decisions.

c. Another aspect is that, generally speaking, airworthiness is demonstrated in a seemingly objective way by analytical methods while qualitative values, which are of a subjective nature, are frequently included in a somewhat hidden form. The corresponding difficulties for submittal and evaluation of a design proposal were briefly discussed in Section 7.2 and it was stated that there is no easy answer except good communication between customer and manufacturer.

   There is a possibility, however, to encourage such communication by a gradual change of emphasis in future specifications.

This may result from a realistic appraisal of past records. Experience, previous performance, and general capabilities of the manufacturer as well as rigid technical specifications and some intangible considerations always have been incorporated in the evaluation of a design proposal -- and yet cost-overruns and necessary modifications after award of a contract have been the rule rather than the exception. Such considerations indicate that no rigid set of specifications can be a safeguard against adverse developments. Therefore, the detail specifications may possibly develop into a somewhat flexible instrument to serve as a guideline for finding the proper balance between a formal procedure and a basic meeting of the minds between customer and manufacturer.

7.4 Summarizing Remarks

a. Among the many aspects of preparing a design proposal, it is believed that submitting meaningful qualitative data and lines of reasoning is of particular importance to the considerations of interface between materials and structures. It will require some cooperation between manufacturer and customer to arrive at a clear and simple system for presenting such information.

b. Some of the comments regarding the role of the military procuring agency and the problem of interface between materials and structures reach into the higher spheres of policy-making. This shows how closely interwoven technological problems and basic policy decisions can be. It also shows how important it is for the engineering community to consider these relationships and to be aware of continuously changing conditions.

The next section will consider another field where technological considerations lead toward far-reaching implications.

8. ACCUMULATION OF EXPERIENCE

8.1 Specialist and Experience

Experience is based on encountering and observing direct impressions and on the resulting "practical wisdom" which is gained. The evaluation of experience was introduced in Section 6.3 as a subject of basic importance in the design procedure and it was mentioned that experience has to be accumulated before it can be evaluated. Some basic aspects regarding the accumulation of experience will be considered in this section.

The specialist acquires confidence by combining basic knowledge and understanding with experience. It seems that experience is generally considered as part of an informal process which is based mostly on the memory of key personnel. By and large, this process has worked quite well. Specialists in the fields of materials, structures, and design have stored in their memories a great amount of experience which they can translate into intuitive evluation of similar situations. Unfortunately, when these specialists die or retire or fade away, all this experience is lost.

An essential aspect is that the detail information which makes up the specialist's experience may be in his mind or in his notebook or in a well-written report -- it is only important that it is available to him. Each specialist requires a different set of data. The materials engineer is concerned to a large extent with test results on different components under various environmental and loading conditions. The structures engineer needs case studies of failures which have occurred in service, particularly failures in unsuspected places. The design engineer needs, perhaps more than anything else, a systematic list of all the many pitfalls which may threaten him at every move.

All such detail information can be collected and made available to those who can profit from it. Any well-written handbook, of course, bears witness to this basic fact. This indicates that experience can be separated from the individual who originally experienced it and can be put on a more general and systematic basis.

8.2 Expanding Technology and Experience

The memory of key personnel has played a dominant role in the utilization of experience because the fast pace of developments is detrimental to keeping a clearly written record of all the many details which can be summarized as experience. However, with an ever increasing number of available materials and structural configurations and with a proliferation of corresponding information, the mental storage capacity of any individual has been exceeded and a record-keeping system will have to be devised.

The situation will become worse in the near future as more new materials become available. It is aggravated by the introduction of composite materials and the consequence will be even more specialization than we have today. This poses a particularly serious problem from the viewpoint of the designer during the early phases of a design. In selecting an optimum combination of material and structure, he has to balance advantages and deficiencies against each other in the fields of many specialists. This requires comparisons on an equal basis which will never be accomplished by depending on random experience of a large number of individual specialists.

Another aspect of the same problem is connected with future optimization methods. Even the most sophisticated mathematical methods are built on quicksand unless they are used on a properly defined problem. For the design problem, experience is one of the basic ingredients and it cannot be incorporated in an optimization procedure as long as it remains ill-defined.

The answer appears to be in the direction of putting individual experience on a systematic basis for comparison and evaluation. This indicates the need to develop an information system which makes accumulated experience available as a first step toward evaluation of experience.

8.3 Competition and Experience

Experience is a valuable asset in the aerospace community and the most experienced company is usually in the best competitive position. Fortunately, there exists an enlightened spirit with regard to competition where agreements about exchange of information among different companies have been negotiated on a management level, where one company may incorporate a potential competitor's engineering package as an entity with corresponding exchange of information, where technical meetings provide for personal contacts and where it is not unusual at all for an engineer to call up an opposite number in another company to exchange information about some technical problems. Another outstanding example for a spirit of cooperation is represented in the workings of the Aircraft Structures Integrity Program (ASIP).

The question is whether we are ready to go a step farther. Regarding an exchange of technical information on materials and structures, each one of the major aerospace manufacturers is in a position to give as well as to take. On this basis, serious consideration should be given to the gradual development of a systematic, industry-wide information system which would contain the type of information which is usually associated with experience, e.g. typical examples for stress corrosion, crack initiation, case studies of failures, etc. Test data on materials and structural components, i. e. more clearly defined data, form a somewhat different category and are discussed in Section 3.5.

Objections from the viewpoint of competitiveness may be overcome by considering that give and take should balance each other in the long run and that competitions are not decided by comparatively small technical details. Objections from the viewpoint of embarrassment about exposing technical mistakes may be overcome by pointing out that there is nobody in a position to throw a first stone.

It is fully realized that such a step will have to be taken judiciously and will require considerable discussion. It may be mentioned that a similar step in the field of material evaluation has been proposed recently (Ref. 18) with special emphasis on the aspect that the overall competitive position of the American aerospace industry may be at stake unless petty considerations of competitiveness can be overcome.

The main problem consists of recognizing the basic nature of the growing complexities before they grow beyond control. This indicates the need for a large-scale, coordinated effort.

8.4 Some Practical Aspects

A large-scale, coordinated effort is frequently associated with large funding requirements. However, this is not necessarily the case. Accumulation of experience requires first of all coordination on a conceptual basis, and a large-scale effort can be provided by proper organization. Neither one requires excessive funding.

After the question of competitiveness was considered from a conceptual viewpoint and appeared to present no obstacles of a fundamental nature, similar consideration can be given to the question of funding. On the working level, accumulation of experience must be implemented by writing up existing experience in a form which provides for easy retrieval. Existing experience is clustered in the minds of a few people in key positions. These people usually have neither time nor inclination to write up their experience in a meaningful way. However, they usually enjoy talking about their experience and answering well-placed questions within reasonable time limits, say about an hour per week. The problem, therefore, boils down to tapping key personnel for systematic information.

The corresponding preparation and evaluation of interviews with key personnel represent a major effort and certainly cannot be done on a haphazard basis. To have these interviews conducted by engineers from the own company or from a competitor would be expensive and might result in some bias. However, there is another possibility which appears to deserve serious consideration.

It was mentioned in Section 5.9.a that our educational system has developed considerable shortcomings with respect to preparing the engineering

student for a future role as a designer, but that some steps have been taken recently toward remedy of this situation. The Engineering Case Method as developed and practiced by the University of California at Berkeley represents one of these steps.

Case studies are conducted in the following manner: Instead of doing experimental or theoretical thesis work, a team of about three graduate engineering students investigates a design problem which has been encountered and solved in industry. Engineers who have worked on the problem are interviewed, all aspects which may have any possible bearing on the problem are thoroughly investigated, and the problem is analyzed and reported in a form which contributes to future knowledge and understanding.

This approach has been quite successful from two viewpoints:

a. The students gain insight and understanding of design problems;

b. industry in general, and the concerned project engineer in particular, get considerable benefit from a report which usually goes into more depth and width of the problem than provided by the available budget, time and manpower of a company.

Such mutually profitable cooperation between industry and universities may be extended to the problem of accumulating experience in the field of interface between materials and structures. A committee consisting of representatives from industry, research agencies, and universities would have to coordinate all efforts, develop guidelines for execution of the work, and evaluate the outcome. The overall problem can be subdivided into subproblems which may be pursued independently but have to follow the same format.

This kind of approach seems to be particularly applicable to gathering and interpreting the type of information which represents our typical experience in the field of design engineering. Problems of crack initiation, stress corrosion, any type of unsuspected failure, examples indicating unforeseen design complexities, etc. fall into this category.

A first step would necessarily be to encourage discussion on the subject of accumulating experience. Long leadtime is involved in this type of work but there is no need to start with a full-scale effort. This indicates that a pilot project along these lines is quite feasible and may be started on a modest scale.

8.5 Summarizing Remarks

Accumulation of experience presents a practical problem of considerable magnitude. As a first step toward its solution, discussion within the

industry regarding exchange of information should be encouraged. Pilot programs on a small scale appear to be feasible.

Utilization of Engineering Case Methods as introduced in engineering education and described in Section 8.4 can provide for a potential dual benefit: accumulation of experience for industry and familiarization with design problems for engineering students. The latter can prepare and motivate students toward a career in design -- a very important aspect in line with the considerations of Section 5.1.

9. CONCLUSIONS

9.1 Summary of Fundamental Problems

A systematic survey of fundamental problems regarding the interaction between materials and structures leads to the following conclusions:

a. The large number of new materials which have to be considered and the increasing sophistication of analytical methods which are at our disposal have taken us to a crucial point where established lines of thinking are rapidly becoming insufficient and inadequate. This situation calls for a fundamental appraisal of our present status and for a far-sighted approach toward an over-all solution.

b. The full impact of interface between materials and structures is encountered during the early design phases before the design is frozen. Basic decisions have to be made during this period when, unfortunately, much of the detail information necessary for analytical solutions is not yet available. This requires experience and reliance on extrapolating previously established data.

c. There are two types of problems which may be considered separately: Firstly, specialized problems of a well-defined scientific or engineering type and, secondly, other more general problems outside the clearly established fields of responsibility.

d. The well-defined specialized problems include fracture toughness, stress corrosion, brittleness, methods of determining residual stresses, non-destructive inspection, testing methods, etc., in the field of materials; finite-element methods, computerization, automated structural design, and optimization in the field of structures; computer-aided methods and value engineering in the field of design. These problems have been clearly recognized and are in the hands of competent specialists within established disciplines. They require no special attention from the viewpoint of interface between materials and structures.

e. The problems which require much attention because they have been somewhat neglected and are not clearly recognized are along the boundary lines between the disciplines of materials, structures, and design and are connected with the need for establishing basic reference data and clarifying the design process.

f. Material application analysis plays a fundamental role in establishing clearly defined conditions and requirements to eliminate misunderstandings between materials engineer and structural designer. Much obfuscation has been prevalent in this field, with general lack of communication as the major cause. The materials

engineer has not been aware of all the structural design requirements, and the structural designer has not been familiar enough with material limitations. A systematic approach must be used to identify requirements in both fields (Section 5.8).

g. Material evaluation techniques must be clearly established in order to form a basis for comparing different materials for structural application. The main problem exists in the field of component testing and much fundamental work is still required (Sections 3.4.4 and 3.4.5).

h. Tests of materials and structural components are conducted in many places but the corresponding large volume of data is not well utilized. Much has to be done with respect to collection, interpretation, storage and dissemination of test data (Section 3.5).

i. A great amount of experience exists in the minds of key personnel. Much of it is poorly utilized and unavailable in places where it is needed. A major reason for this situation is the lack of time and opportunity for top people to disseminate their experience. Earnest consideration should be given to possible remedies (Section 8).

j. Hardly any attention has been paid yet to the field of human engineering factors which enter the design process. Qualitative values, evaluation of experience, and judgment have to be considered in addition to the presently recognized reliability, maintainability, and risk evaluation before it will be possible to identify the technical decision process which holds the answer to the problem of interface between materials and structures (Section 6).

k. Three widely separated fields which have caused some general concern recently should be considered for their connection with the basic problems of interface between materials and structures: One is the slow rate of utilization of new materials in aerospace structures (Section 3.6); the second one is the need for educating engineers along lines which make them aware of overall responsibilities beyond their specialized fields (Sections 5.1 and 8.5); the third one is the changing situation in the aircraft industry as the number of new types of aircraft has been reduced, their complexities have been increased, and the former reliance on prototype models has been eliminated.

l. The problem of interface between materials and structures has many aspects. It is of immediate and dominant importance for the utilization of new materials in aerospace structures. In the

near future it will assume a major role as the design process has to be clarified due to increasing complexities. In the more distant future it will have to be solved as a prerequisite for using more sophisticated methods of structural optimization.

9.2 Major Problem Areas

A general consideration of these conclusions indicates that the dominant problem consists of not yet having recognized the full significance of some fields which are outside our clearly established responsibilities. They may be defined as follows:

a. There is an outspoken gap between the results of materials R&D and the requirements for applying new materials to aircraft production. This is the main problem connected with the utilization of new materials.

b. There is a growing need to make systematic use of experience and to express qualitative design considerations in terms of quantitative values. This is the main problem connected with the design process. More work in this field is required in order to establish controlling parameters for the selection of material and structural configuration.

c. There is the latent fact that fundamental transitions are taking place in aircraft design. Corresponding implications on the interface of materials and structures deserve additional consideration.

These aspects are of basic importance for solving the problem of interface between materials and structures. There are no fundamental obstacles in any of these fields but solutions will require considerable time. Any postponement multiples the difficulties. Neither crash programs nor large-scale funding are deemed advisable, but there is a definite need for discussing various implications and taking essential steps in the right direction. The following recommendations should be considered from this viewpoint.

10. RECOMMENDATIONS

The preceding conclusions resulted in identifying three regions of concern with respect to the interface of materials and structures on airframes (Sect. 9.2). Based on the considerations shown in the report, the following recommendations are made for these regions:

10.1 In order to bridge the gap between the results obtained from materials R&D and the requirements for applying new materials to aircraft production,

a. it is recommended to establish a basic system for material application analysis as outlined in Section 5.8;

b. it is recommended to define typical components which can be service-tested on existing aircraft and can be designed and manufactured by utilizing different methods and which can serve as the basis for a full comparison;

c. it is recommended to intensify efforts toward obtaining uniform material evaluation techniques for component testing as summarized in Section 3.4.5;

d. it is recommended to give full consideration to the development of a test data information system as outlined in Section 3.5;

e. it is recommended to consider the conclusions of the NASA Research and Technology Advisory Subcommittee on Materials (Section 3.6) as the most authoritative findings regarding the problems of utilizing new materials;

f. it is recommended to unify these diverse aspects under a coordinating committee which would establish guidelines and evaluate results while responsibility for execution of the work should be properly delegated. This committee should include representatives from government agencies, research organizations, and aerospace industry, representing materials engineers as well as structural designers.

The recommendations may be implemented

for items 10.1.a and 10.1.b by proceeding along similar lines as initiated but discontinued under the former AFML project "Basic Shapes";

for item 10.1.c by subdividing the overall problem into well-defined sub-problems, inviting proposals for their solution and sponsoring corresponding projects;

for item 10.1.d by emphasizing the basic importance of the problem and encouraging and sponsoring corresponding efforts.

These detail suggestions are tentative and should be verified or modified by the coordinating committee. There is an urgent need for action which has been generally recognized recently and the situation is ripe for it. The initiative will have to come from government sponsorship.

10.2 In order to clarify the growing need for expressing qualitative design considerations in terms of quantitative values and for making systematic use of experience,

a. it is recommended to increase visibility for qualitative design considerations by showing the corresponding line of reasoning in engineering analysis whenever this is applicable (see Sections 6 and 7);

b. it is recommended to give full consideration to the subject of utilizing available experience as outlined in Section 8;

c. it is recommended to start pilot programs on Case Studies of design experience which can be used as examples for a systematic accumulation of experience as outlined in Section 8.4.

Implementation of these recommendations would be mostly the responsibility of the aircraft industry. Basic considerations regarding competition and experience will have to be decided on a policy-making level. Evaluation of qualitative values will require much systematic work.

10.3 In order to appreciate how fundamental transitions taking place in aircraft design are related with the field of interface between materials and structures, the following considerations are suggested:

a. The lack of prototype aircraft will necessitate provision for prototype components for flight evaluation on existing aircraft (as it is being done by the Air Force on the composite program).

b. The high cost of developing new materials and correspondingly different structures as well as establishing substantiating data will make it important for each new development to be based on a clear recognition of the interplay between experience and vision.

c. The increasing complexities of high-performance aircraft make it necessary to transform the conventional design process, which is partly intuitive and empirical, into a systematic approach

showing rationale.

d. Interrelations between the fields of materials, structures, design, production, maintenance, and economics have to be integrated in the design process and require an awareness of problems which may lie beyond well-defined fields of responsibility.

e. As a final consideration:

Interface between materials and structures is concerned with finding an optimum combination of material and structure. This represents the essence of the structural design problem. It requires fundamental decisions during the early phases of the design process when input data for refined analytical methods are not yet available. These decisions have to be based to a large extent on experience and judgment but, despite much analytical sophistication in engineering, considerations regarding experience and judgment are taking place on a rather primitive level.

Experience and judgment involve understanding which has to be based on systematic information. A prodigious amount of information is being accumulated but its systematic use depends on considerations of competitiveness and the atmosphere in which it takes place. Major developments usually assume the form of competition among peers. Capabilities of personnel, capacities of plant and equipment, and similar considerations, have become the dominant factors; technical details are rightfully expected to conform to the highest standards. Yet this is possible only if there is a good exchange of technical data. Some promising trends can be recognized as a consequence of widening horizons. Further developments along these lines are important for solving the interface problem between materials and structures.

TABLE 1 (from Ref. 1)

MATERIAL PERFORMANCE CHARACTERISTICS

MECHANICAL PROPERTIES

- TENSION
  - Stress Strain Curve
    - To 0.2% offset
    - Complete curve
  - Tensile Properties
    - Ultimate
    - Yield
    - Elongation
    - Reduction of Area
- MODULUS OF ELASTICITY
  - Static Tensile
  - Static Compression
  - Modulus of Rigidity
  - Dynamic Modulus
  - Poisson's Ratio
- COMPRESSION
  - Stress Strain Curve
    - To 0.2% offset
    - To 0.5% offset
  - Compressive Properties
    - Yield
- BEARING
  - Stress Deformation Curve
  - Bearing Properties
    - Yield
    - Ultimate
- SHEAR
  - Ultimate
  - Shear Yield in Torsion
- FATIGUE STRENGTH
  - Smooth
  - Notched (K_t = 3.0)
  - Fretting
  - Rolling Contact
  - Corrosion Fatigue
- CREEP
  - 0.1%
  - 0.2%
  - 0.5%
  - 1.5%
  - Rupture
- CRACK PROPAGATING RESISTANCE
  - Notched Tensile Ratio (K_t = 3.0)
  - Definition

Notched Rupture Ratio (K_t = 3.0)
Definition
K_{1c}
K_c
Slow Flaw Growth

IMPACT RESISTANCE
V Notch Charpy

WEAR RESISTANCE
Galling
Abrasion Resistance
Erosion

STRESS CORROSION
BALLISTIC IMPACT
DAMPING
CAVITATION
SPALLING

PHYSICAL

DENSITY
HARDNESS
COEFFICIENT OF FRICTION
VAPOR PRESSURE
VISCOSITY
POROSITY
PERMEABILITY
REFLECTIVITY
TRANSPARENCY
OPTICAL CHARACTERISTICS
DIMENSIONAL STABILITY

THERMAL

CONDUCTIVITY
SPECIFIC HEAT
COEFFICIENT OF EXPANSION
EMISSIVITY
ABSORPTIVITY
MELTING POINT
ABLATION RATE
FLAMMABILITY

ELECTRICAL

DIELECTRIC CONSTANT
HYSTERESIS LOSS
CONDUCTIVITY

NUCLEAR

- HALF LIFE
- CROSS SECTION
- STABILITY

CHEMICAL AND METALLURGICAL

- CORROSION
- BIOLOGICAL
- THERMAL STABILITY
- CRAZING
- OXIDATION

FABRICABILITY

- WELDABILITY
- MACHINABILITY
- HEAT TREATABILITY
- FORMABILITY
- FASTENERS

FORMS

- SHEET
- PLATE
- BAR
- EXTRUSION
- FORGING
- CASTING

DETERIORATION

- METALLURGICAL

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13. ABSTRACT

The interface of materials and structures is of particular importance during the early design phases of an aircraft when decisions regarding the choice of material and corresponding structural configuration have to be made. This part of the design process is considered from the viewpoints of materials, structures, and design engineers. While well-defined problems in each of these fields are in the hands of competent specialists, it is shown that major problems also exist in the ill-defined regions between these specialties and have beckoned vainly for any systematic approach toward their solution. These problems are identified and steps toward their solution are recommended in some detail.

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